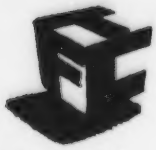

DCIEM No. CR 2001-070

INTERIM REPORT - SUMMARY OF PHASE 2 ACTIVITIES

Project:
Development of an Aluminum Fuel Cell Power Source for a Diver Heating System

by:
G.D. Deuchars

Fuel Cell Technologies Ltd.
20 Binnington Court
Kingston, Ontario K7M 8S3

Project Manager:
J.H. Stannard
613-544-7374

PWGSC Contract Number:
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on behalf of
DEPARTMENT OF NATIONAL DEFENCE

as represented by
Defence and Civil Institute of Environmental Medicine
1133 Sheppard Avenue West
North York, Ontario, Canada
M3M 3B9

DCIEM Scientific Authority:
David Eaton
416-635-2086

March 30, 2001

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EXECUTIVE SUMMARY

This report describes the second phase of a program to develop a Diver Heating System (DHS). The technology selected for the power supply was the aluminum-oxygen fuel cell. An aluminum anode is oxidized in the presence potassium hydroxide electrolyte when supplied by oxygen from a conventional diver's oxygen storage and regulator equipment. The fuel cell is approximately 50% efficient. The heat rejected to the electrolyte is recovered in a heat exchanger, and the electrical output is also converted to heat.

During this phase of the work, a pumped system was developed, after a trade-off analysis showed that a pumped system had significant cost and logistical advantages over the type of cell stack developed in phase one of the work. The electrochemical performance of the cell stack and the technical feasibility of this type and design of fuel cell had been proven in phase one of the work, but the development of a pumped system represented a significant departure from the previous phase 1 work.

The system was designed, built and successfully tested in the presence of the scientific authority. The system was tested underwater, and delivered 500 Watts of thermal output for a period of 5 ½ hours. The test demonstrated the integration of all of the required subsystems of the fuel cell, but did not include integration of the fuel cell with the diver heating system (DHS) developed by Delta Temax. Delta Temax were unable to provide a unit tailored to the 12 Volt output of the fuel cell in time for system integration and final testing. However, integration with the heating system is not considered a technical risk, and can be accomplished in the next phase of the work.

This report summarizes the design, subsystem development, and test results for the fuel cell. Also included are recommendations for further work, which will form the basis for a proposal for the phase 3 activities required to develop an Advanced Design Module.

Sommaire

Ce rapport décrit la seconde phase d'un programme visant à mettre au point un système de réchauffement pour plongeurs. On a choisi la technique de la pile à combustible aluminium-oxygène pour obtenir l'énergie. Une anode en aluminium, baignant dans un électrolyte d'hydroxyde de potassium s'oxyde en présence d'oxygène fourni par les appareils classiques, réservoir d'oxygène et détendeur, du plongeur. La pile à combustible est efficiente à 50 p. 100. La chaleur refoulée vers l'électrolyte est récupérée dans un échangeur et l'électricité produite, convertie en chaleur.

Durant cette phase du travail, on a créé un système de pompage après qu'une analyse comparative en a révélé les avantages considérables, du point de vue coût et logistique, par rapport à la batterie de piles qu'on avait conçue au cours de la phase 1. Le rendement électrochimique et la faisabilité technique de la batterie de piles à combustible étaient éprouvés pendant la phase 1, mais la mise au point d'un système de pompage a apporté un grand changement de méthode par rapport à la phase 1.

Le système était conçu, fabriqué et testé avec succès en la présence du responsable des questions scientifiques. On l'a testé sous l'eau et on a constaté qu'il fournissait une puissance thermique de 500 W en cinq heures et demie de temps. Le test a prouvé l'intégration de tous les sous-systèmes essentiels de la pile à combustible mais pas l'intégration de la pile à combustible munie du système de réchauffement pour plongeurs (DHS) conçu par l'entreprise Delta Temax. En effet, cette dernière n'a pas pu fournir à temps un dispositif adapté au courant de sortie de 12 V de la pile à combustible pour le test d'intégration et le test final du système. Toutefois, on estime que l'intégration au système de réchauffement ne présente pas un risque technique et qu'on peut l'effectuer à la phase suivante.

Ce rapport résume les travaux de conception et de mise au point des sous-systèmes de la pile à combustible ainsi que les résultats des tests subis par celle-ci. Y sont aussi incluses les recommandations pour le travail à entreprendre plus tard, recommandations qui serviront de base à la proposition des activités nécessaires à la réalisation du module perfectionné au cours de la phase 3.

1.0 INTRODUCTION

This report summarizes the design and performance testing of a fuel cell for the diver heating system. In the previous phase of the work, a system had been developed that consisted of 9 separate cells, each containing enough electrolyte to support the electrical output of the cell for the 6 hour discharge, and a stainless steel tube through which water from the diver heating system flowed. The heat transfer from the electrolyte to the flowing water was achieved with a thermosyphon flow of the electrolyte past the cooling tube.

The phase two work was originally to refine the design of the cell stack, design an oxygen delivery system, and integrate the system with the diver heating system (DHS) developed by Delta Temax. At the request of the scientific authority, FCT undertook a comparison study of the unpumped cell stack design with a system more like FCT's other underwater systems, in which the electrolyte is stored in a separate sump, and is pumped through a cell stack. The comparison was completed, and it was determined that there were compelling cost and logistical advantages to the pumped design. At that point the design changed to a pumped design. This necessitated a completely new cell stack design, a shell-and-tube heat exchanger to remove heat from the electrolyte as it was pumped through the cell stack, design of an oxygen supply regulator, design of a pump and pump enclosure that was housed in the electrolyte sump, design of the sump itself, and integration of all of these systems inside an insulated enclosure suitable for testing underwater.

This report summarizes the development of these subsystems, the subsystem tests carried out to determine the performance of the subsystems, and the final tests of the overall system.

One of the other goals of this project was to integrate the fuel cell with the diver heating system developed by Delta Temax. This would have used the electrical output of the fuel cell to provide approximately 250 Watts of electrical power to a modified 12 volt DHS, and would also integrate the coolant loop to allow flow of the coolant through the fuel cell, where an additional 250 Watts of heat would be removed. The DHS was not available in time for integration with the fuel cell for final testing.

2.0 TRADE-OFF STUDY

2.1 Introduction

A trade-off analysis was carried out to compare a pumped and an unpumped fuel cell for this application. The first step in the analysis was to determine the criteria to be used for comparison. Of interest to the customer was the volume and mass of equipment that had to be transported in order to achieve a number of dives in one location. Another key element was cost. The trade-off also looked at logistical considerations, and the requirements of the various subsystems for both designs.

For the comparison of shipped volumes and mass, it was assumed that the end-user would want to ship enough cell stacks to provide for 20 complete discharges of the system at a particular location. It was also assumed that the cost of the unpumped system was $2500 versus $5000 for the pumped system. The additional cost of the pump and heat exchanger required for the pumped system were the basis for the increased cost of the pumped system. Although these figures are rough estimates, the analysis quickly showed that the advantages were clear enough to eliminate the need for a detailed cost breakdown.

The results of the comparison are shown in Table 1. The following sections describe the derivation and meaning of the results.

2.1.1 System Volume

The volume of the unpumped system was based on the final design of the phase 1 cell stack, and included insulation and packaging of the cell stack required for operation in cold water. It did not include the oxygen sphere or the DHS. The volume calculated for the pumped system was based on a preliminary design of the system, which included a sump of the required volume, a cell stack, and the required insulation.

The major advantage of the pumped system becomes apparent when we calculated the shipped volume in order to achieve 20 discharges. Because the cell stack for the pumped system is so small compared to the other system, the total shipped volume is only 78.3 liters, compared to 584 liters for the unpumped system.

2.1.2 System Mass

The same analysis was carried out for the shipped mass to achieve 20 discharges, and the results showed that the pumped system totaled 56.5 kg, versus 170

kg for the unpumped system. This differences in overall mass and volume would become more significant if the system were to be shipped by air to remote locations.

2.1.3 Cost

The capital cost of the two systems was assumed to be $2500 for the unpumped system (this includes a structure containing oxygen regulator, hydrogen removal check-valves, and insulation) and $5,000 for the pumped system. The cost of the cell stack was assumed to be $400 for the unpumped system and $150 for the pumped cell stack. This is primarily because of the difference in materials costs, and because the pumped stack is much more complex due to the heat exchanger tubes and associated piping. The differences in cost per discharge for 20 and 200 discharges are shown in Table 1. The capital cost of the system is amortized over the number of discharges for each system. It is clear that over the life of the system, the cost per discharge is significantly less with the pumped system.

Parameter	Unpumped	Pumped
System Volume (l)	29.2	21.4
20 Discharges	584	78.3
Mass (kg)	8.5	6.5 + 2.5
20 Discharges	170	56.5
Cost		
Capital Cost	$2,500	$5,000
Per Discharge	$400	$150
20 Discharges	$525/discharge	$400/discharge
200 Discharges	$412.5/discharge	$175/discharge
Logistics	Large stack volume to neutralize	Small stack volume to neutralize
Safety	Stacks must be shipped to FCT after use	Stacks are disposable after neutralization
H2 management	Need H2 removal from both ends of stack	Only one H2 removal port required
O2 management	Need O2 Quick-connects on all stacks	O2 Supply piping connected to cylinder
Thermal management	Need water quick-connects on all stacks	Water piping connected to electric heater
KOH Supply	Need fixed volume of KOH to fill stacks	Need fixed volume of KOH to fill tank
Pressure Compensation	Need pressure compensation for each stack	Need pressure compensation for tank only

Table 1 Results of Trade-off Analysis

2.1.4 Logistical Considerations

One important consideration in the eventual field use of this system is that after each discharge, the cells or sump must be drained of spent caustic, and the cell stack must be neutralized with carbon dioxide to stop any hydrogen production from the anode surfaces.

For the pumped system, it is relatively easy to add neutralizer directly to the sump, and circulate this through the cell stack in order to effectively neutralize the stack and the caustic. The caustic would then have a neutral pH and can be disposed of easily. The cell stack and sump can then be purged with CO2 as a way of removing any hydrogen present, and to ensure that the stack hydrogen production has been stopped. For the unpumped system, the caustic would have to be removed from the cell stack into a separate container, and then neutralized separately. This would leave a relatively large volume to purge inside the cell stack, and the anodes would take considerably more CO2 to neutralize completely because they will have caustic with a high pH on their surface. Another consideration is that this cell stack would be difficult to ship back to a central site to recover the expensive piping and fittings required for the thermosyphon system, because of safety concerns about the potential for hydrogen production and/or the presence of caustic.

A significant advantage of the pumped system is that the cell stacks are relatively inexpensive, and can simply be disposed of after use.

A number of other design issues were considered in the analysis, but the conclusion was that the pumped system is less expensive, and much smaller and lighter to transport in quantity to any location. The decision was made to proceed with the design of the pumped system after the completion of this analysis and a presentation of these results to the scientific authority.

3.0 SUBSYSTEM DEVELOPMENT

This section outlines the development of the subsystems or components that make up the fuel cell. They include the following:

- Cell stack
- Thermal management
- Oxygen supply
- Electrolyte sump
- Electrolyte pump
- Hydrogen removal and buoyancy compensation
- Insulation and Packaging
- Electrical

3.1 Cell Stack

The basic design parameters for the cell stack remained the same as the previous phase, as the electrochemical performance had already been well proven. The stack was designed similar to other cell stacks at FCT, and incorporates materials that are inexpensive and easy to machine. The quantity of cells to be manufactured during this demonstration phase was far too low to justify a molded cell design, so they were designed to be machined from 3mm thick foamed PVC material. FCT has used this material in other cell stack applications, and its properties are well proven for the application. An exploded view of an individual cell is shown in Figure 1.

Each individual cell is made up of four pieces of machined PVC, two cathodes, and one anode. The cathode is sandwiched between two pieces of PVC (shown as blue and yellow), with the inside pieces (shown in blue) designed to hold the anode in place, and to form an electrolyte inlet and outlet flow passage when the two cell halves are bonded together. Urethane adhesive is used between the four pieces of PVC, and assembly jigs were used to line up the cell frames using the electrolyte inlet and outlet holes as reference points.

Prior to being sandwiched between the two pieces of PVC, a bus bar is soldered to the nickel strip on the edge of the cathodes. PEM (spell out—it is not a common term) fasteners are used to connect adjacent cathodes together, and to connect the cathodes of one cell to the anode of the adjacent cell. A complete single cell is shown in Figure 2.

The cells were assembled and glued in the assembly jigs, and removed after the urethane was set. Then the holes for the through bolts (used to hold the stack together with end plates) and oxygen supply holes were drilled. The cell stacks are assembled

by stacking up 9 cells together with gaskets between cells to seal the electrolyte and oxygen flow passages. The stack is held together with endplates at either end, and four through bolts were used to hold the stack together. It was found during testing that the plastic endplates did not have enough rigidity, and they were backed up with two pieces of 1/8" thick stainless steel. A completed cell stack is shown in Figure 2. On the left endplate, electrolyte inlet and outlet fittings (shown in blue) and oxygen inlet and outlet fittings (shown in white) attach to the endplates with standard pipe thread fittings. These mate with O-Ring fittings on the electrolyte sump. The electrical connections were sealed in potting compound, with a wet-pluggable connector wired through the endplate into the potting compound. This connector mated with a connector on a junction box used for the electronics.

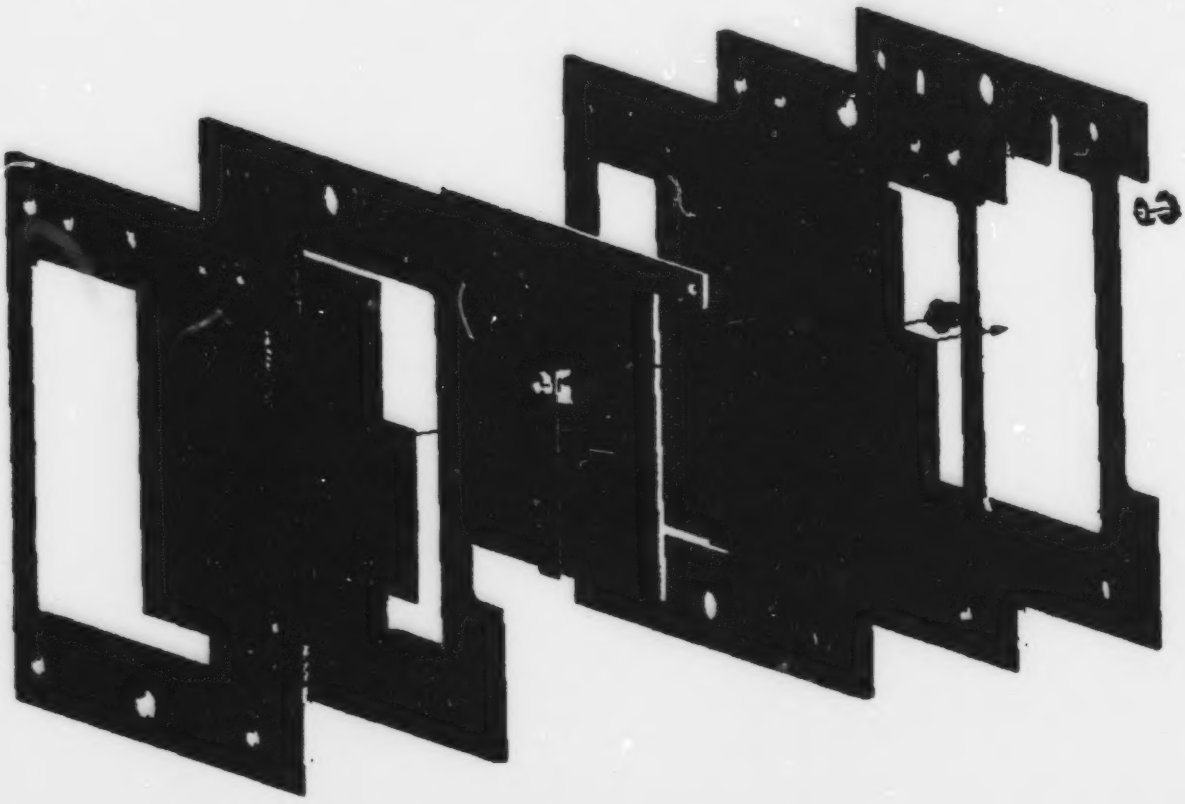

Figure 1 Exploded View of Single Cell

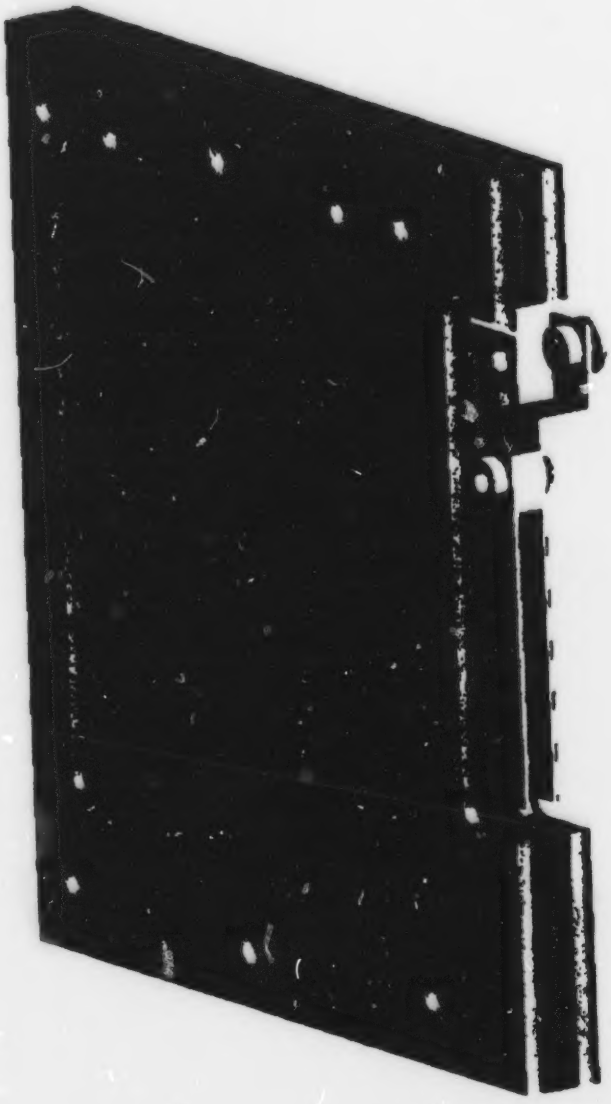

Figure 2 Single Cell

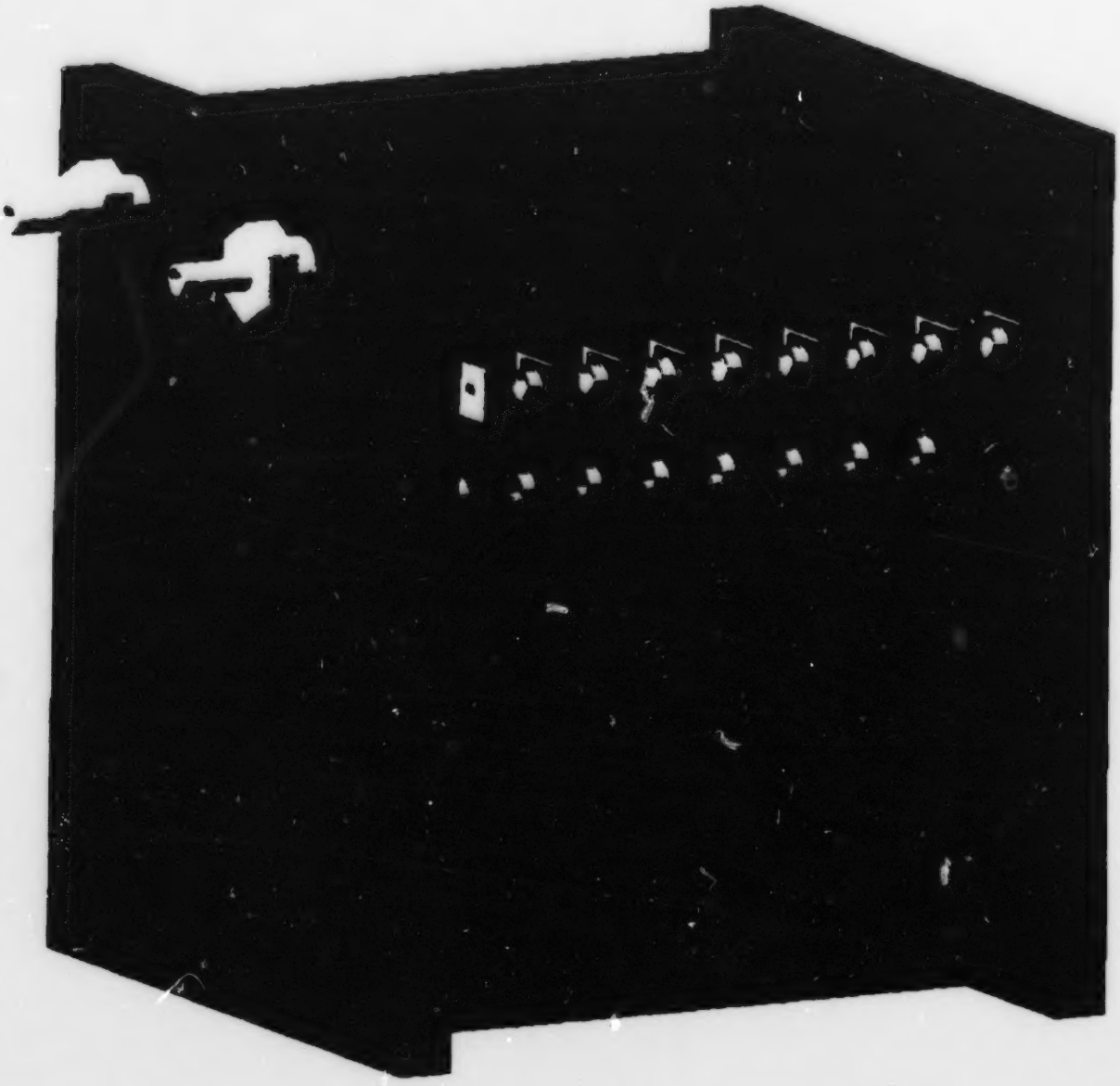

Figure 3 Complete Cell Stack

3.2 Thermal Management

In order to remove the heat produced by the electrochemical reaction, and maintain the electrolyte temperature in the 50 to 60°C range, a shell-and-tube heat exchanger was sourced. The heat exchanger is a nickel brazed, stainless steel heat exchanger modified by the supplier (Exergy Inc.) to fit in the electrolyte sump.

A test was undertaken to verify the performance of the heat exchanger at the appropriate water and electrolyte flow rates. The overall goal of the heat exchanger performance is the removal of up to 250 W of heat from the flowing electrolyte at these operating conditions. A chiller unit was set up to maintain the water flowing through the heat exchanger at a constant temperature corresponding to the return temperature from the diver, and a valve and rotameter were used to control the flow rate of the water to approximately 1 l/min. An analysis of performance estimates for the chosen heat exchanger at water flow rates of 2, 3, 4, and 5 l/min and a curve fit to the data showed that the heat exchanger performance will be degraded by only 6% if the water flow rate was reduced from 1 l/min to 0.5 l/min.

A controlled temperature bath heater unit was used to heat the electrolyte to a temperature of 50 to 60°C, and the electrolyte pump used for the system was used to circulate the electrolyte through the heat exchanger at approximately 5 l/min.

The results from this test are shown in Figure 4. The graph shows the water and electrolyte inlet and outlet temperatures, and the calculated heat removal rate. All of the thermocouples used in the tests were calibrated prior to the test. The thermocouples were calibrated using ice water and water at 60°C, with the readings checked to establish accuracy within + or -- 0.1 °C.

The results show that the heat exchanger can remove in excess of 250 Watts of heat from the electrolyte. The performance of the heat exchanger was actually higher than that predicted by the supplier at the specified flow conditions.

The overall design of the electrolyte flow loop involved the flow from the electrolyte pump entering the heat exchanger, and the exit flow from the heat exchanger then going to the cell stack. This prevented any backpressure created by the heat exchanger being imposed upon the cell stack.

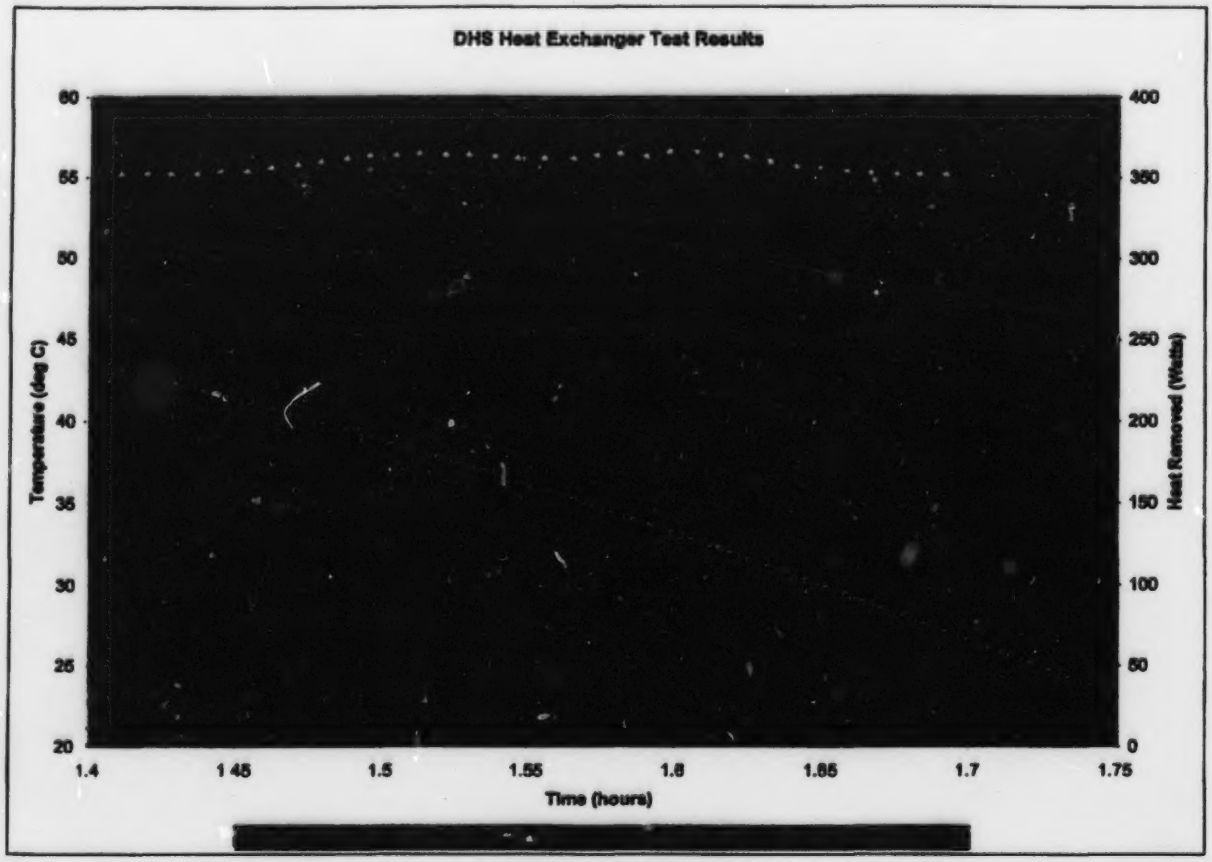

Figure 4 Heat Exchanger Test Results

3.3 Oxygen Supply

The cell stack requires a flow of oxygen regulated to a pressure of approximately 4" w.g. This is to balance the electrolyte pressure in the stack (caused by the outflow of electrolyte from the stack and hydrostatic pressure) to the oxygen pressure in the oxygen cavities between cells. An off-the-shelf diving regulator was purchased (Aqua Lung Conshelf XIV Regulator), and its performance was evaluated. The components in the diving regulator were used in the design of the fuel cell regulator, and a complete housing was machined from stainless steel, which included the required inlet and outlet fittings, as well as a diaphragm adjustment screw used to set the pressure over a range of 0 to 20" w.g. Different springs were tested in order to provide the appropriate range of pressures. Tests were then performed with the regulator underwater to verify that it could provide the required flow of oxygen (from 0 to 600 ml/min @stp) while maintaining the required pressure. The tests were successful, and the regulator was mounted on the side of the fuel cell and supplied with oxygen at 80psi. The regulator is capable of

functioning at the standard 150 psi supply pressure as supplied from the oxygen sphere and regulator supplied by DCIEM, but the pressure was limited to 80 psi because of pressure limitations of the rotameters used to verify the oxygen flow for the fuel cell tests.

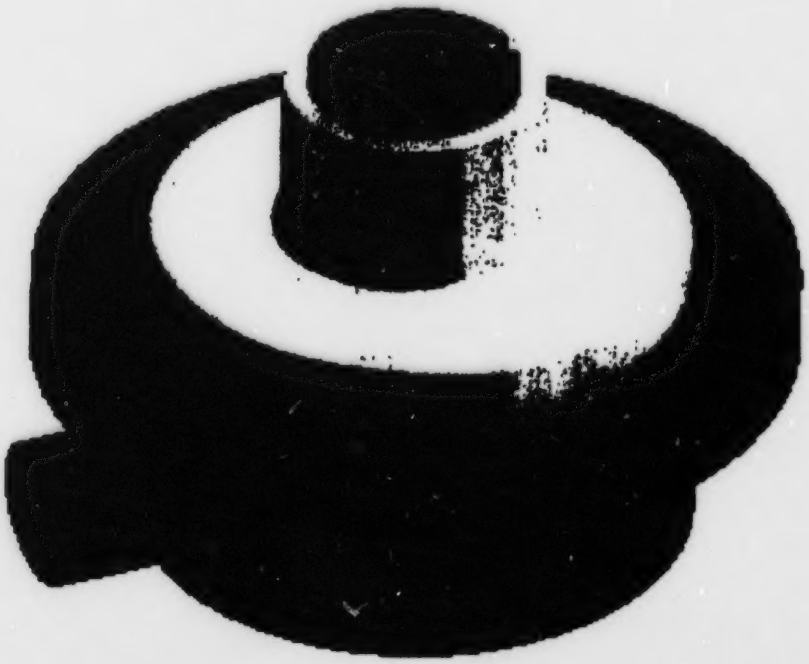

Figure 5 Fuel Cell Oxygen Regulator

3.4 Electrolyte Sump

The electrolyte sump was manufactured from stainless steel for this prototype system. The sump was designed to house sufficient electrolyte for a 6-hour discharge, the electrolyte pump, the shell-and-tube heat exchanger, and all of the piping and fittings required to circulate electrolyte to and from the cell stack. The top of the sump had to accommodate the hydrogen removal check valve, water inlet and outlet fittings, a fitting to connect the wiring to the electrolyte pump (the wires run through an oil filled tube), oxygen inlet and outlet fittings and an electrolyte fill port. Plastic bulkhead fittings were used where possible, sealed to the electrolyte sump with O-ring seals. One side of the electrolyte sump was used to mount a buoyancy compensation bladder, which has four fittings to allow seawater and air in and out of the compensation bladder. After all of the required fittings were located and the sump designed, an outer jacket of insulation was added, which had to accommodate all of the fittings and penetrations while maintaining a

good thermal barrier. The front of the electrolyte sump had a removable plate to allow for installation and servicing of the equipment inside the electrolyte sump. The overall assembly of the electrolyte sump, including all of the fittings attached to it is shown in Figure 6.

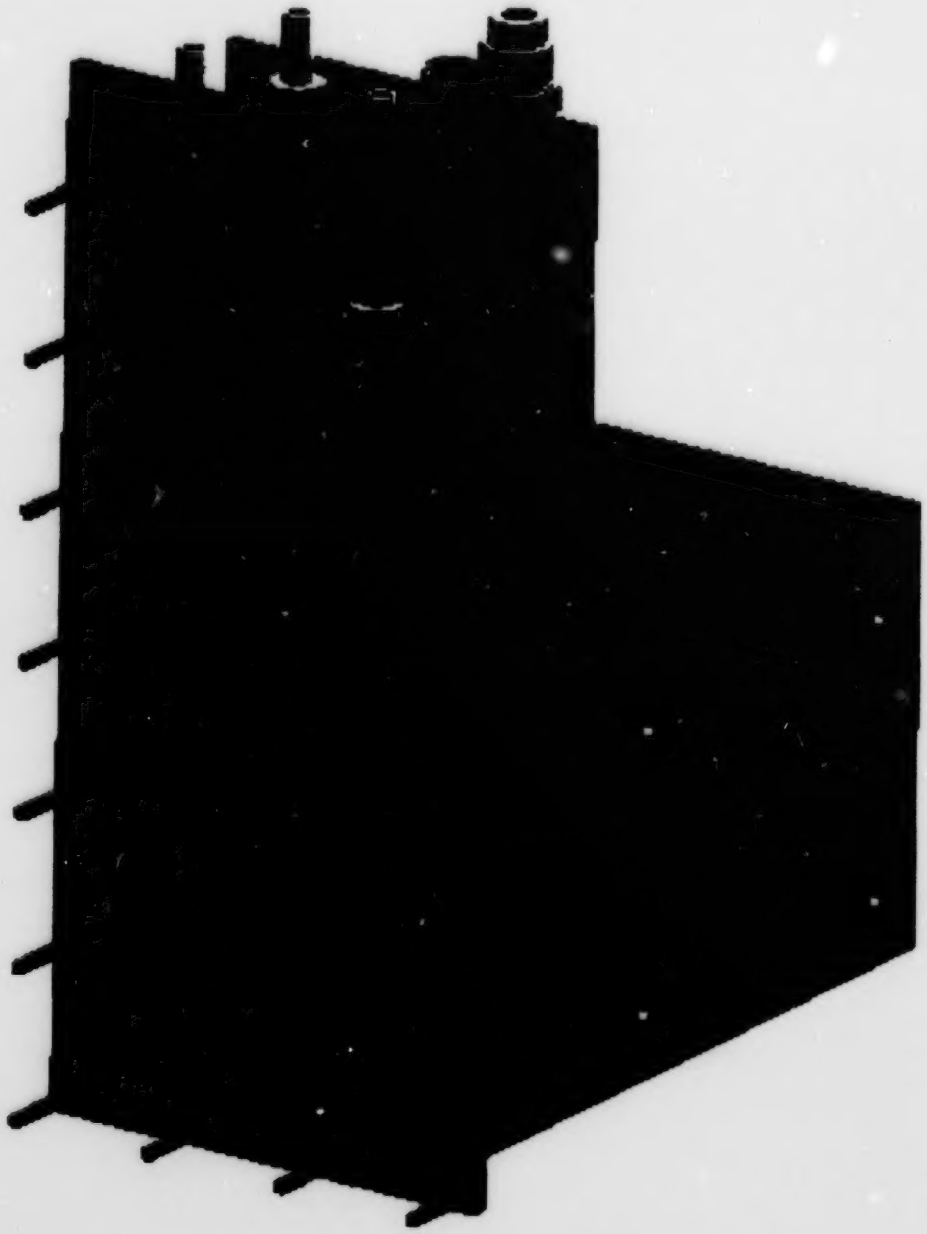

Figure 6 Sump Assembly

3.5 Electrolyte Pump

The electrolyte pump chosen for the application was the same type of pump used for other underwater systems at FCT. A Micropump centrifugal pump (pump head model #G101-000) with a brushless DC motor drive (Integral series 0024) was housed in an oil-filled enclosure, and located at the bottom of the electrolyte sump. The pump has variable speed control, controlled with a 0 to 5 volt input signal, and runs on a 24 VDC supply. The manufacturer did not have a 12 Volt version of the integral series pump, which would have been preferrable. A small DC-to-DC converter was used to supply the 24 Volt supply to the pump, and a variable 0 to 5 volt control input was added (using a small transformer and trim potentiometer) in order to vary the control voltage. The pump and the oil-filled enclosure are shown in Figure 7.

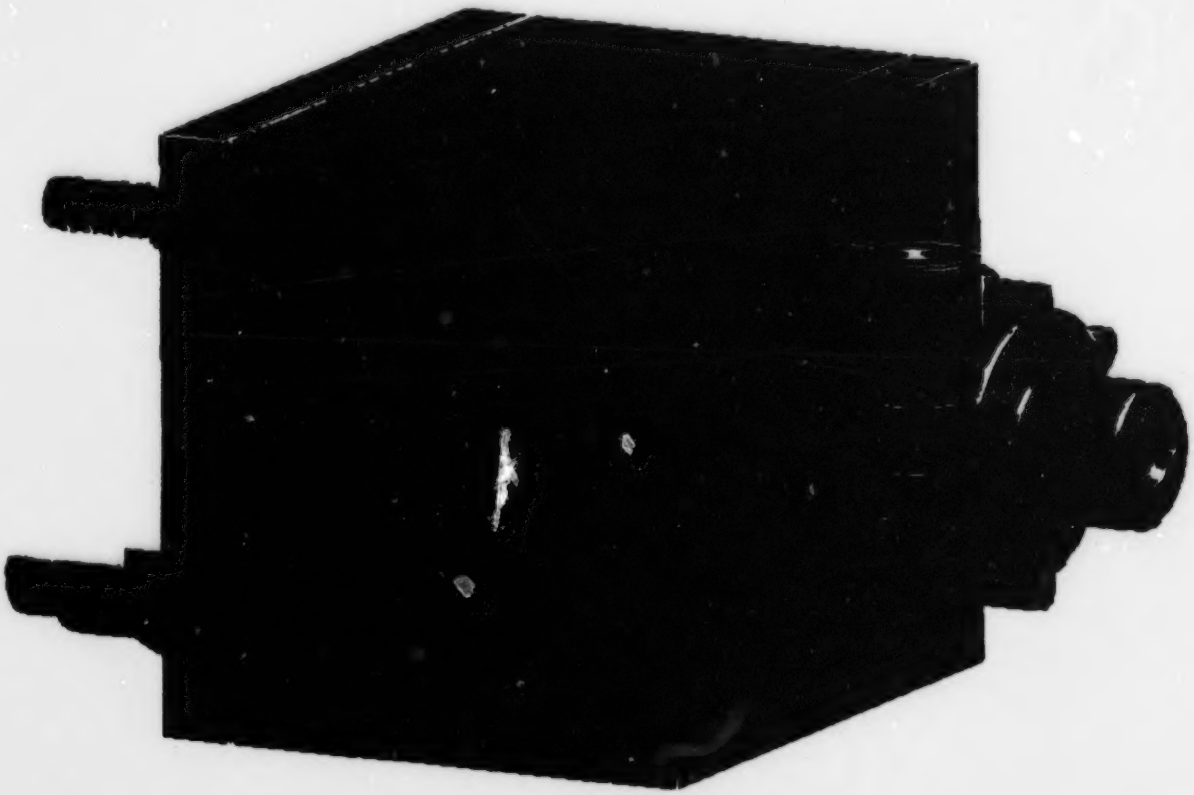

Figure 7 Electrolyte Pump and Enclosure

The white fitting at the bottom of the enclosure is a quick-connect fitting used to fill the enclosure with silicone oil, and the black fitting at the top is used to pass the wires through to the motor. The motor is sealed inside the enclosure with an O-ring seal.

3.6 Hydrogen Removal and Buoyancy Compensation

A one-way check valve us used to allow hydrogen to leave the electrolyte sump as it bubbles out of the flowing electrolyte. By simply connecting the outlet of the check valve to a u-shaped pipe that points downward, a volume of gas is trapped in the U-tube. This allows the gas to flow through the check valve without seawater entering the valve every time the poppet rises from the seat of the check valve.

A buoyancy compensation bladder is incorporated into the electrolyte tank. This bladder is connected through the wall of the tank at two points at the top and bottom of the bladder to allow seawater to enter and exit the bladder. During a rapid descent of the system, it is possible that the rate of hydrogen production is less than the rate of compression of the gas trapped inside the top of the electrolyte tank. Under these conditions seawater flows into the compensation bladder, making up for this discrepancy in volumes and balances the pressure of the system to the ambient pressure of the seawater. When the fuel cell reaches the end of the shot line and is fixed in place, the system re-establishes the volume of hydrogen at the top of the electrolyte tank while the bladder is pushed flat against the side of the electrolyte tank. Tests were performed to verify proper functioning of the check valve and compensation bladder combination, and no significant changes in pressure resulted.

3.7 Insulation and Packaging

One of the biggest challenges was the integration of all of this equipment inside a relatively small space, and then insulating the entire package so that in seawater of temperatures as low as -2°C the overall package would lose less than 50 Watts of heat with the electrolyte at 60°C. An outer jacket of foamed PVC material was made and attached to the electrolyte tank with urethane adhesive. The area at the top of the electrolyte tank was difficult to properly insulate, because of the number of fittings and piping and the irregular shape of the housing at the top. The use of a metal electrolyte tank made the insulation of the overall system much more difficult, because it was not possible to eliminate contact between the tank and the water. Further design development is required to solve these problems, with a plastic sump being the most likely option for the design.

Figure 8 shows the overall system with one wall cut-away and the front cover plate removed. Figure 9 Shows the overall system without the insulating cover that was used to insulate the cell stack.

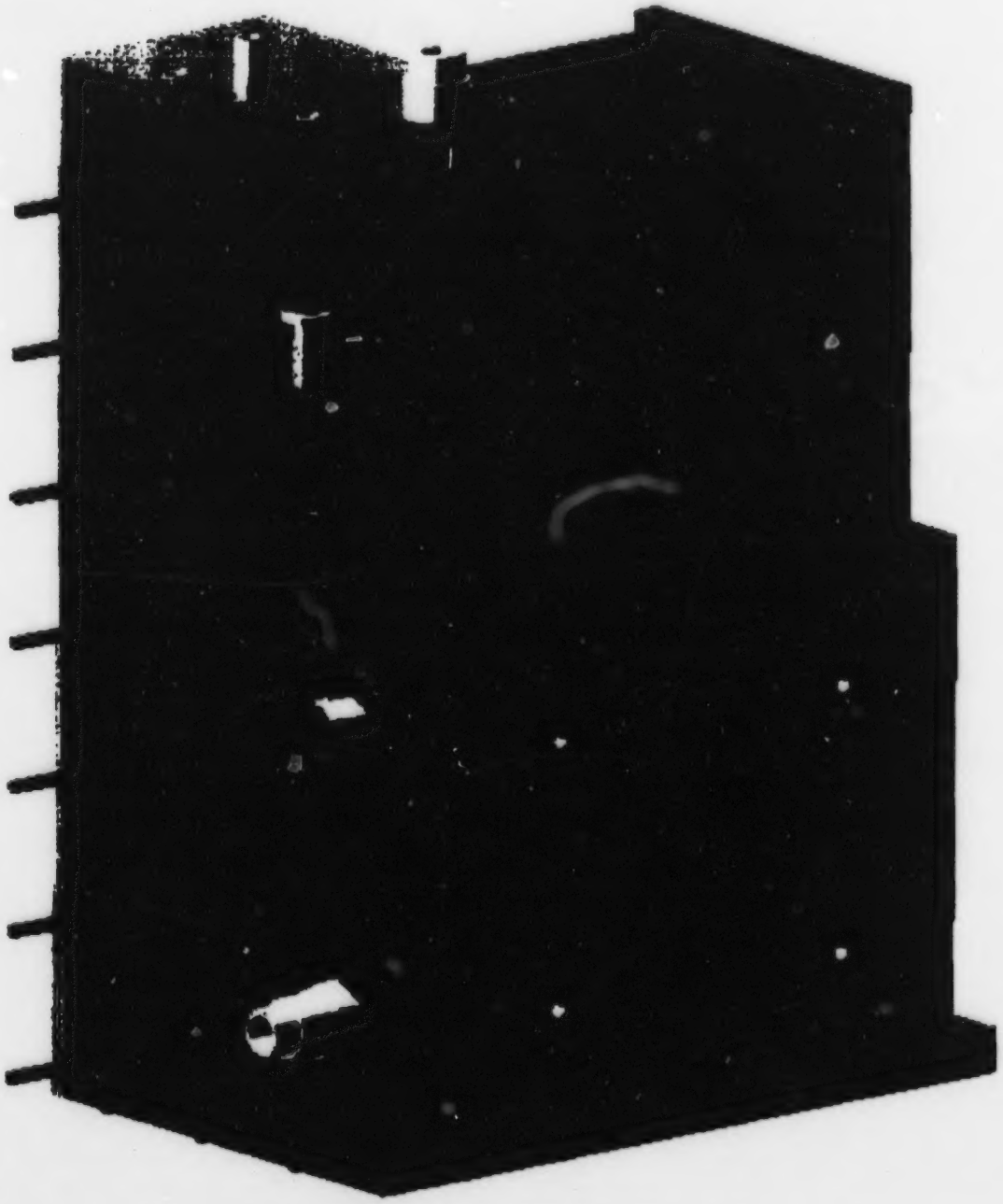

Figure 8 Cut-away View of Overall System

Figure 9 Overall System Without Cell Stack Cover

3.8 Electrical Design and Packaging

An oil-filled enclosure was used to house the electronics for the electrolyte pump, and connectors and wiring to allow start-up of the fuel cell and integration with the DHS. The wiring enclosure schematic is shown in Figure 10.

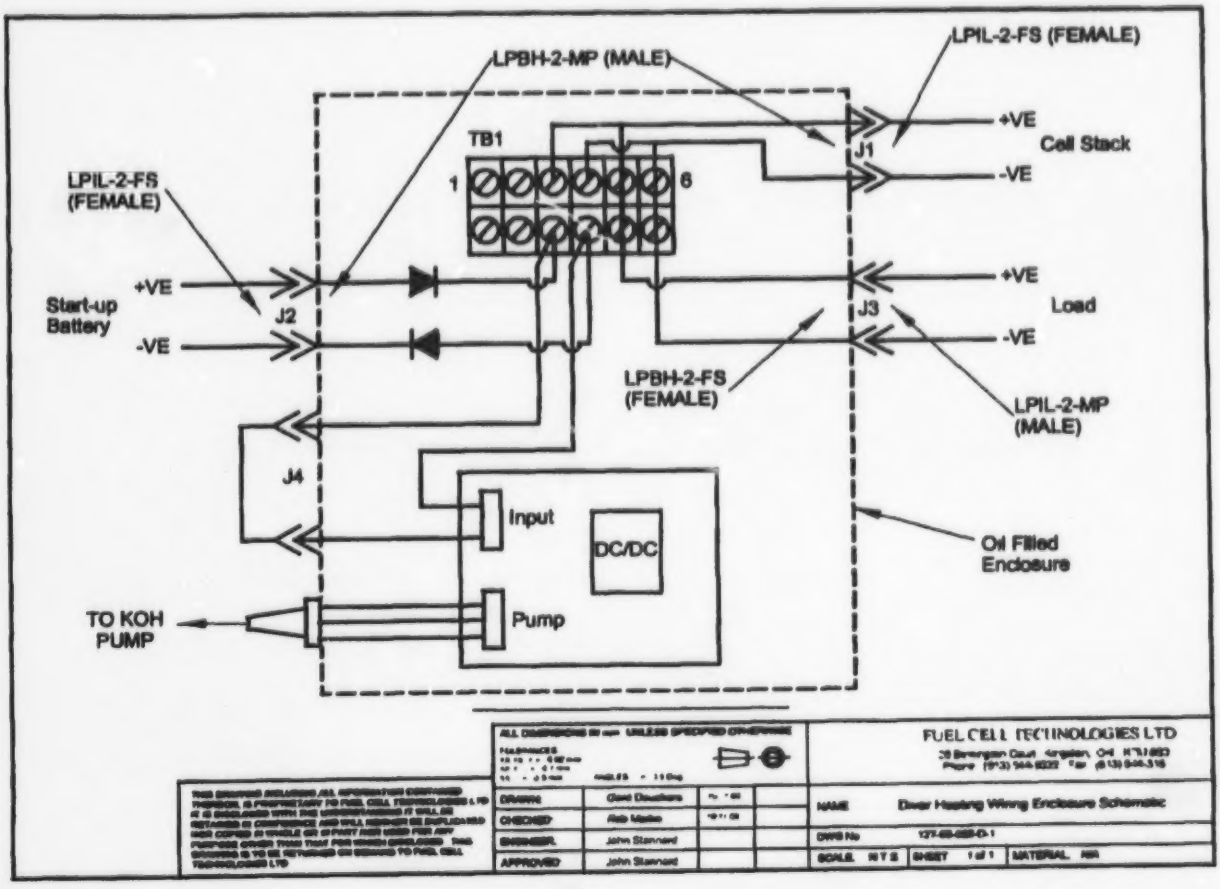

Figure 10 Wiring Enclosure Schematic

To start the electrolyte pump, a jumper plug (J4) is first installed, and an external battery is then connected via another wet-pluggable bulkhead mounted connector (J2). As soon as the electrolyte pump circulates electrolyte through the battery and oxygen is flowing to the cell stack, the cell stack output supplies the power for the pump and the start-up battery or power supply can be removed. The 12 to 24V DC-to-DC converter and a separate 0 to 5 VDC control voltage output is fed to the electrolyte pump through an oil filled tube that connects to the fuel cell and travels through the electrolyte to the electrolyte pump.

Connector J1 us used to connect the output of the cell stack to the enclosure, and the connection to the load (the DHS system) is done via connector J3. The enclosure and connectors are shown in Figure 11.

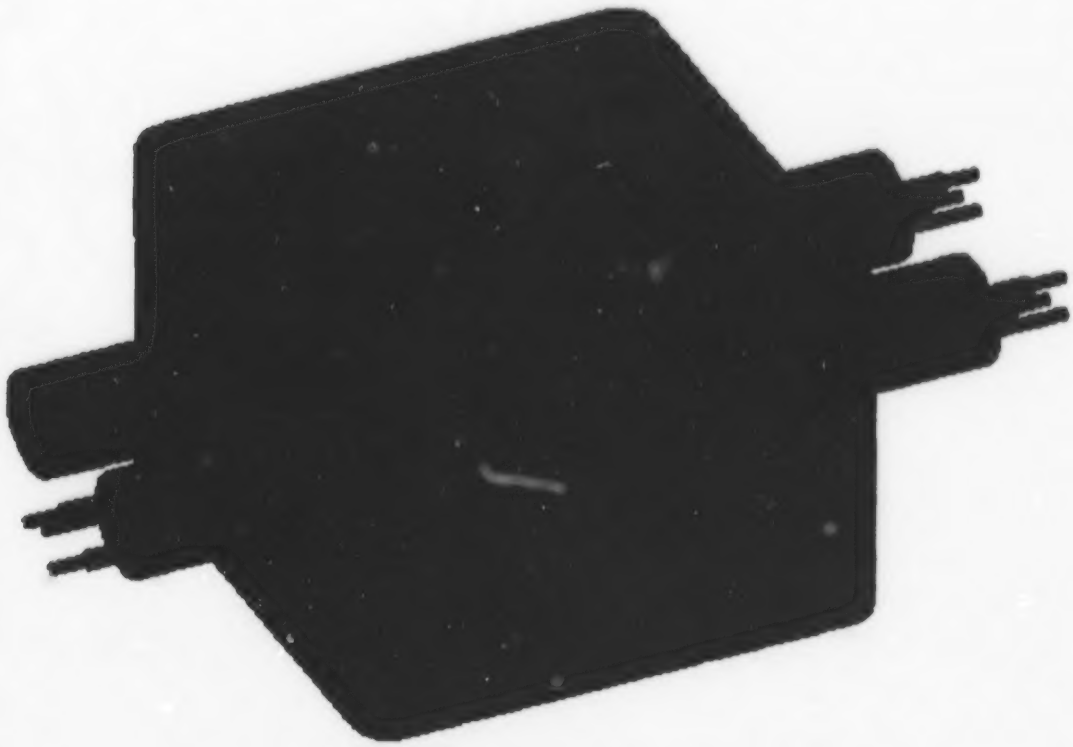

Figure 11 Electrical Junction Box

4.0 PERFORMANCE TEST RESULTS

Three performance tests were carried out in order to verify the overall performance of the system. The final test was performed in the presence of the scientific authority. This section describes the tests performed.

4.1 Test Apparatus

The fuel cell test rig consisted of the equipment shown in Figure 12. A large tank was set up to test the fuel cell underwater. The electrical output of the cell stack was connected to an electronic load, which was manually varied in order to achieve the appropriate power output. Coolant (water) was circulated through the fuel cell heat exchanger from a chiller unit, which controlled the temperature of the coolant to the desired level.

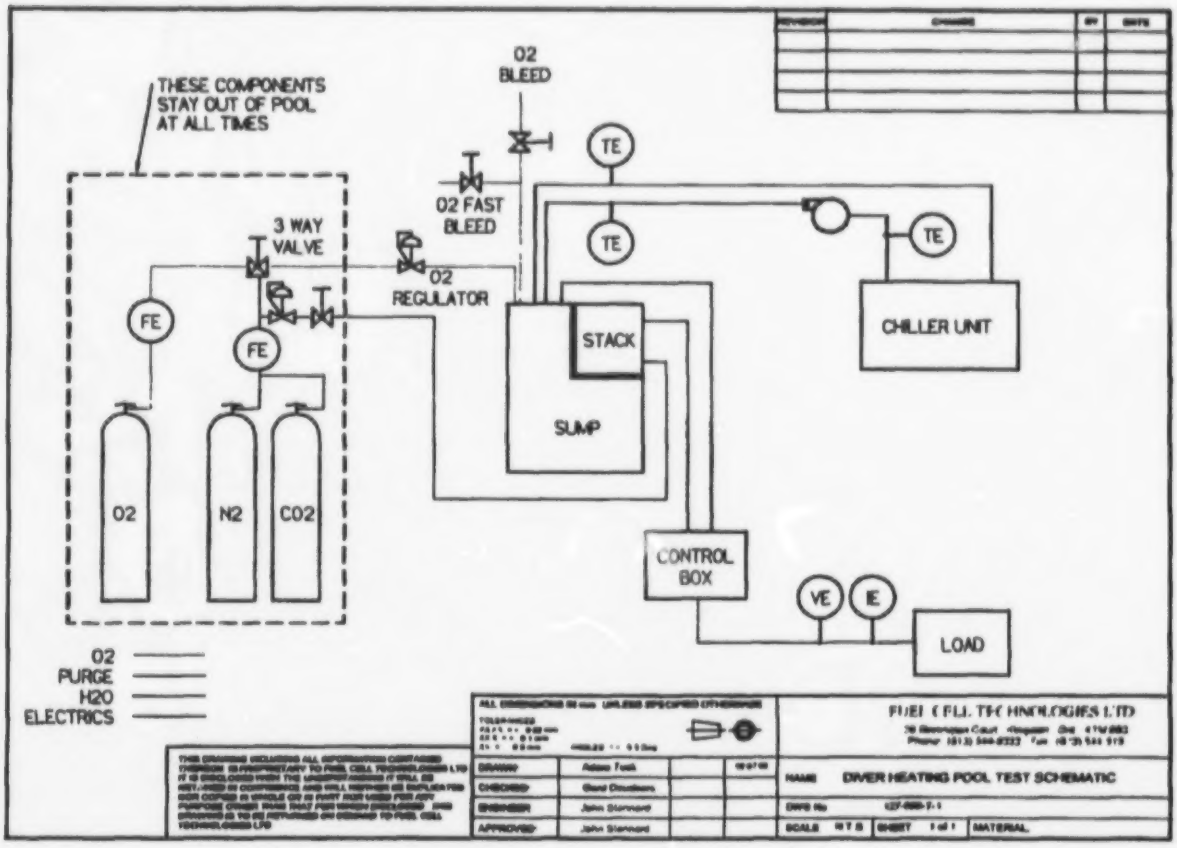

Figure 12 Test Rig Schematic

The inlet and outlet temperature of the coolant was measured with thermocouples located at the inlet and outlet of the cell stack. It was found during the first test that the insulation around these thermocouples was not adequate, and the insulation was increased during the final tests. Tests were performed to verify that the temperature of the test tank did not affect the thermocouple readings. The oxygen supply to the stack was supplied from an oxygen bottle with a regulator set to 80 psi. The flow of oxygen was measured by flowing the oxygen through a rotameter.

The electrolyte-containing (wet) side of the cell stack and the oxygen-containing (dry) side of the cell stack were connected to a purge system capable of purging the wet and dry side of the stack with either nitrogen or carbon dioxide. While being purged, gas entering the wet side of the stack exited the cell stack from the electrolyte outlet piping, entered the top of the electrolyte tank, and exited the tank via the hydrogen vent valve. This enabled a purge of the wet side of the stack and the electrolyte tank prior to pumping caustic through the cell stack.

The exit fitting of the dry side of the cell stack was connected to two different valves. One of the valves allowed for a high rate purge of the cell stack, while the other valve was used to set a slow bleed rate during testing. The high rate purge valve had two purposes. While purging the cell stack prior to flowing electrolyte, this allowed any air trapped in the cell stack to be removed quickly with nitrogen from the nitrogen purge supply. Also, when the electrolyte pump was turned on, and it was desired to draw current from the cell stack, the nitrogen in the cell stack could be quickly purged out and replaced with oxygen with the use of the high rate purge. During normal operation of the cell stack, the high rate purge valve was closed, and the purge rate was set to approximately 10% of the oxygen flow rate. This was to eliminate the build up of water vapour or inert gasses in the dry side of the cell stack, which had proven to reduce cell stack performance in previous systems. These precautions were taken during this testing because our experience with this system was limited, and it is our policy to purge both sides of a cell stack prior to testing.

A test plan and start-up procedure was written prior to the tests, and is included as Appendix A.

4.2 Results of Test #1

The first test of the system took place on March 09/01. The start-up procedure was followed, and after the electrolyte pump was started and the oxygen flow established at the appropriate pressure, the external power supply used to start the pump was disconnected and the system powered itself.

The load was increased as fast as possible while maintaining the measured stack voltage above 10 Volts. Several factors became apparent:

- We had not installed an electrolyte temperature probe, which would allow us to see how fast the electrolyte temperature was increasing,
- The apparent performance of the cell stack was poor, and the stack did not seem to be able to support a load higher than 125 Watts, even after the coolant inlet and outlet flow rates indicated that the electrolyte temperature was in the correct range,
- When we put the cell stack underwater, the coolant inlet and outlet temperature probes were obviously affected by the temperature of the tank, as they changed immediately upon immersing the system underwater.

After trying to run the system for several hours, a decision was made to halt the test, store the cell stack underwater to keep the electrodes fully wetted, and try to resolve the test rig issues. When removed from the system, it was found that the dry side of the cell stack contained electrolyte, indicating that there was an internal leak in the cell stack allowing electrolyte into the dry side of the stack.

The following changes were made prior to starting the test for the second time:

- The coolant inlet and outlet thermocouples were covered with a thick layer of foam insulation, and the performance of the thermocouples in the water bath was verified.
- A check valve was installed in the electrolyte side purge line, as electrolyte had traveled up the purge line and filled the supply regulator to the wet side purge line

The test was re-started, and after the coolant temperatures indicated that the electrolyte was in the appropriate temperature range the fuel cell was still apparently unable to supply much more than 125 Watts of electrical power.

At this point in the test, the wet side purge line was disconnected, and it was found that the electrolyte pressure in the stack was about 40" w.g. This is far in excess of that allowable, and it was thought that this high pressure had flooded the electrodes with electrolyte and had caused the poor stack performance. The test was stopped, and a potentiometer was installed to allow a variable output control voltage to the electrolyte pump. The electrolyte pump speed was adjusted until the pressure on the wet side of the stack was in an appropriate range, and the test was resumed. The performance of the stack was still poor, and the test was halted. It was thought at this point that the electrodes were flooded with electrolyte, resulting in poor performance.

4.3 Test #2 Results

A second cell stack was built, and the following changes were made to the fuel cell and test rig prior to the second test:

- Thicker stainless steel backing plates were made and used to retain the cell stack endplates when the through bolts were tightened,
- A thermocouple was added to the electrolyte sump to allow a direct measurement of electrolyte temperature,
- The purge piping and control valves were improved to make the operation of the purge system considerably easier,

The second test was started, and the load was increased steadily while maintaining a stack voltage of at least 10 Volts. It was difficult to increase the electrolyte temperature to the range of 50 to 60°C, and the measured stack performance was still poor. After several hours of trying to debug the test rig, it was noticed that the voltage was being measured at the load, and when the voltage was measured at the individual cell level (holes were drilled in the potting compound in order to read the cell voltages), it was discovered that the stack voltage was within normal limits, but the voltage drop between the cell stack and the load was very large due to the size of the power leads. Tests were done to quantify the voltage drop over a range of currents, and an appropriate function was added to the software to correctly predict the voltage output of the stack while still measuring the voltage at the terminals of the load.

After this change was made, it was possible to increase the load to the appropriate level; the electrolyte temperature rose to the appropriate range, and the cell stack was operated at a total power output of 500 Watts for three hours.

4.4 Test #3 Results

A third cell stack was constructed, and a third test was carried out in the presence of the scientific authority. The cell stack was started up, and the load was steadily increased while maintaining the stack voltage above 10 Volts. The electrical, thermal and total power output of the system are shown in Figure 13, as well as the accumulated energy output of the system during the test. At the beginning of the test, the electrical load was increased steadily while maintaining the stack voltage above 10 VDC. The total output of the system (thermal and electrical) reached 500 Watts within half an hour of start-up, and the system was then placed in the water tank for the duration of the test.

During the first 3 ½ hours of the test, the electrical power output was consistently higher than the thermal output, while the total power output was maintained at 500

Watts. At the 3.6 hour mark it was decided to reduce the coolant flow rate from 1 l/min to 0.5 l/min, to see the effect on total power output. In order to properly quantify the effect, the electrical load was kept constant during this period. The thermal output went through an initial dip, increased to a steady-state level about 15 Watts lower than achieved at the higher flow rate. At the 4.7 hour mark, the water flow rate was increased to 1 l/min and remained there for the duration of the test.

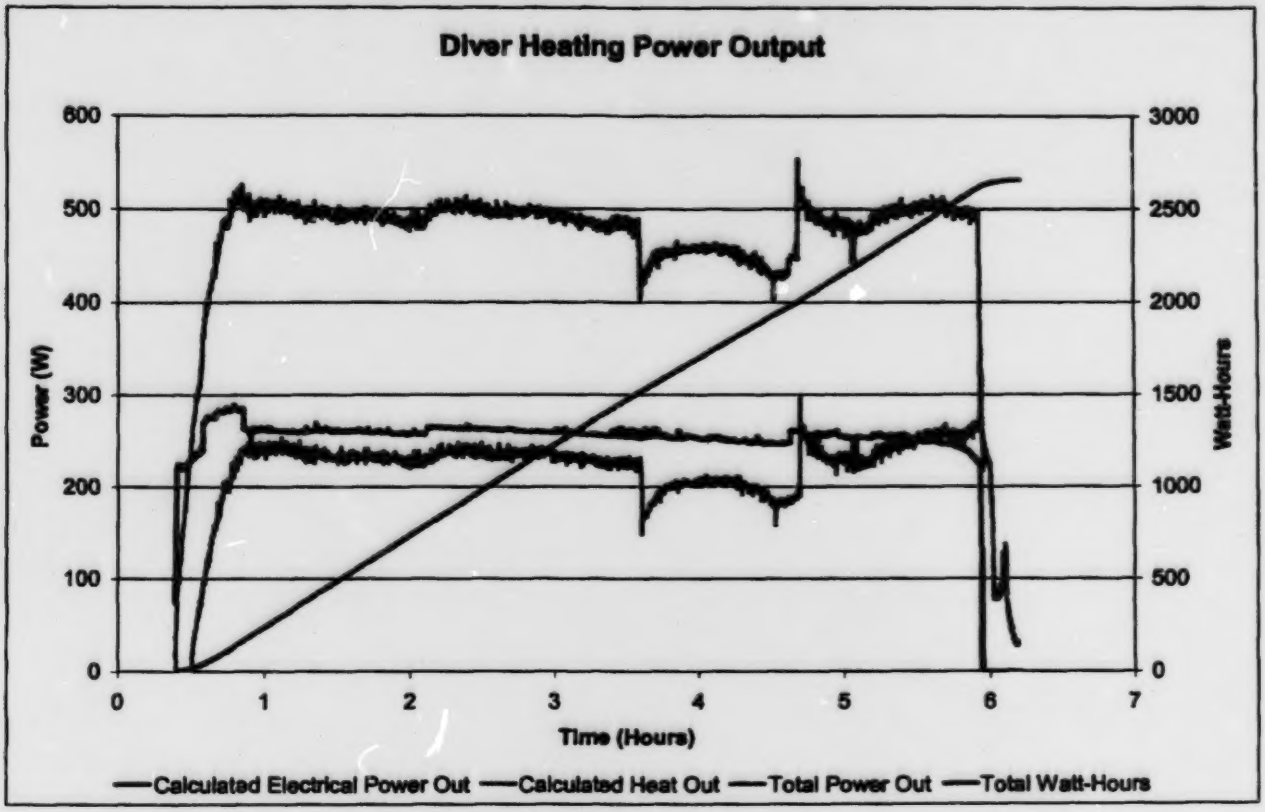

Figure 13 Test #3 Power and Energy Output

The electrical performance of the cell stack is shown in Figure 14. The stack provided more than 250 Watts of electrical for most of the test, except the last half an hour, during which the thermal power exceed the electrical power. The thermocouple installed to measure the sump temperature failed at the beginning of the test, so no data is available to indicate the electrolyte temperature during the test.

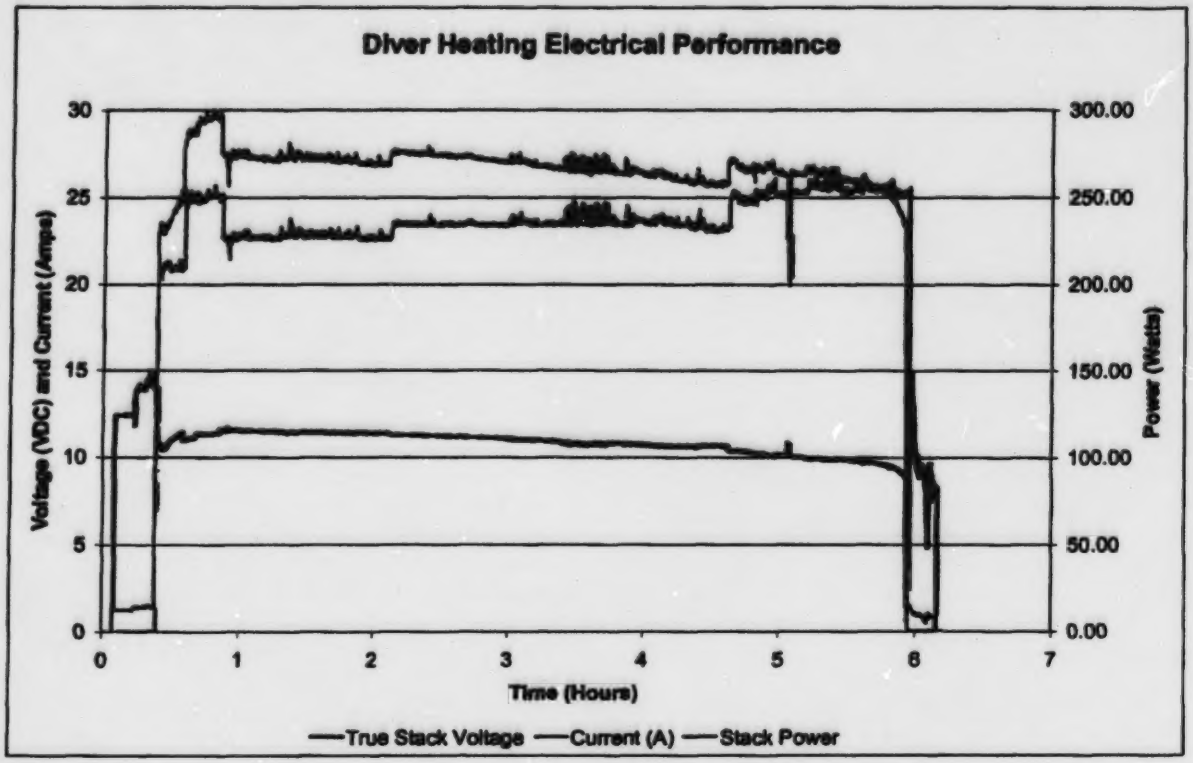

Figure 14 Electrical Performance

It should be noted that the overall goal of the project was a net power output of 450 Watts of power delivered by the fuel cell, assuming a gross power output of 500 Watts and an average loss of 50 Watts of heat from the fuel cell itself. During the test, the *net* power output was adjusted to maintain 500 Watts. For the entire 5 ½ hour test, the net power output of the system was in excess of 450 Watts, and for most of that time the net output was approximately 500 Watts.

In order to quantify the heat lost by the fuel cell to the water bath, a comparison was made between the theoretical heat output of the cell stack versus the heat actually removed by the cooling water. The theoretical heat production is calculated as follows:

Heat (Watts) = (9 * 2.73 Volts – Stack Voltage) * Current (Amps)

(The theoretical Al/O2 potential is 2.73 Volts, and the stack has 9 cells).

The difference represents heat loss to the surrounding water bath. The results of this analysis are shown graphically in Figure 15.

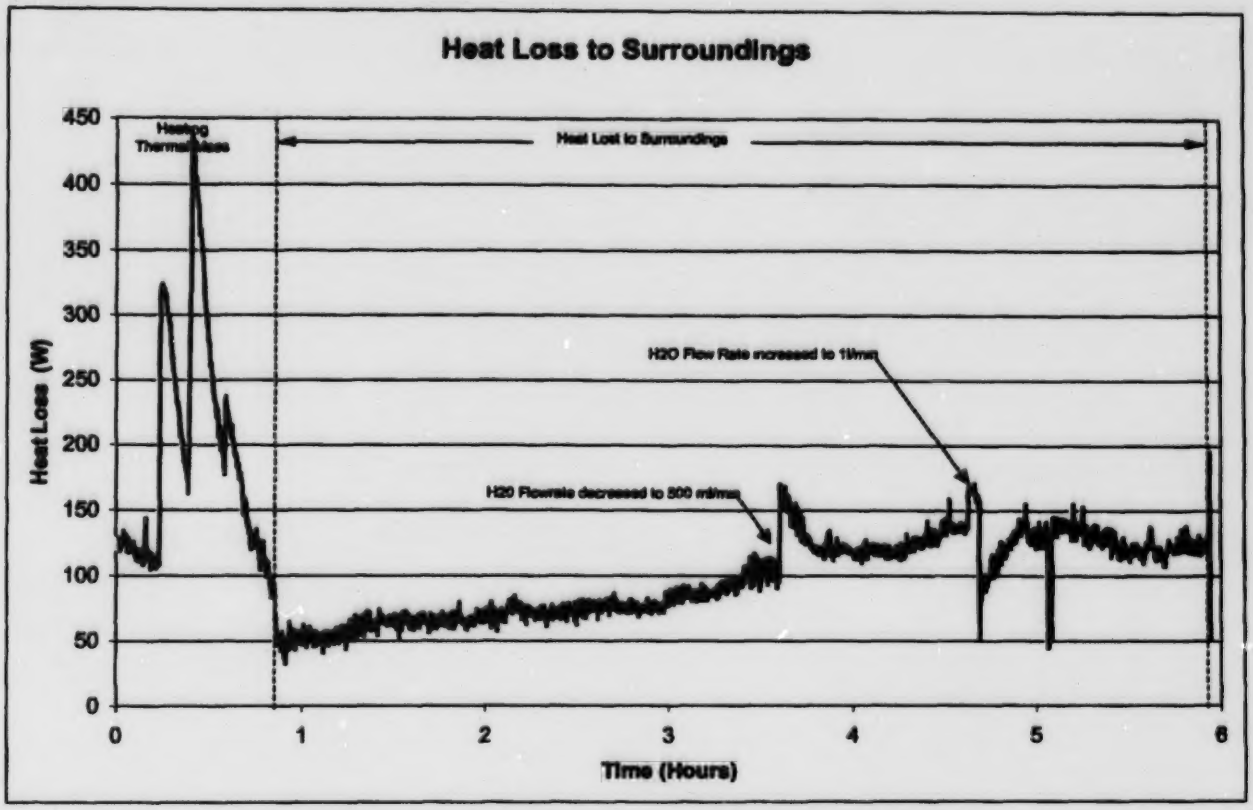

Figure 15 Calculated Heat Loss to Surroundings

During the period when the electrolyte was being heated up, the calculations shows an apparently high heat loss, but this actually represents the heat used to increase the temperature of the electrolyte to the proper operating point.

At the 0.8 hour mark, the system reached a total power output of 500 Watts, at which point the load was set to a constant current, and the electrolyte had reached its appropriate operating point. The heat lost by the system is represented by the data to the right of the vertical line on the graph. The heat loss can be seen to gradually increase during the test (which probably corresponds to a gradual increase in electrolyte temperature), reaching levels in excess of 100 Watts at the end of the test. The period during which the coolant flow was reduced is indicated on the graph. The average heat loss from the system during the entire discharge was 96.5 Watts. Given the fact that the temperature of the water bath was at about 20°C, as apposed to a seawater temperature of about 0°C, it is clear that the insulation of the system must be improved.

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 Overall Performance

The prototype system developed and tested during this phase of the work clearly demonstrated the technical feasibility of this power source, and demonstrated a high level of system integration in one overall package. The system delivered a total of 2.7 kW-hours in an underwater test, with no operator intervention required at any stage of the test, except for the period between 3.6 and 4.7 hours during which the coolant flow rate was changed for research purposes. The prototype nature of the overall design, including the fact that the electrolyte sump was manufactured from stainless steel, resulted in a higher than expected heat leak from the system. This reduced the overall performance because of the loss of energy to the surroundings, and also because this necessitated a higher electrical output from the cell stack than would be required from a more insulated enclosure. This is not considered a technical risk, and would be addressed during further development.

It was not possible during this phase of the development to power the DHS already developed with the fuel cell electrical power output because of time constraints. Regardless of this fact, the use of an electrical load during the final test was adequate to quantitatively demonstrate the performance of the system.

The majority of the mechanical design issues have been resolved during this phase of the work. Some minor design issues remain, but the remaining design issues are more related to logistics of operation, safety, and final packaging.

The gravimetric and volumetric energy density of the fuel cell itself (not including an oxygen sphere) works out to the following:

- 80.2 W-hrs/liter
- 97.5 W-hrs/kg

This level of energy density can be achieved with a relatively low cost per discharge. Further development of this power source will result in a system that meets the performance of more exotic battery technologies at a fraction of the life cycle cost.

5.2 Recommendations

The next phase in the development of this system for underwater and/or above ground use would require the design and testing of an advanced development model (ADM). The development of the ADM would require the following work to be carried out:

- Further testing of the prototype system, integrated with a modified 12 Volt DHS, in order to fully quantify the system performance over a range of operating points and to experiment with design improvements where possible,
- Further development of all subsystems, where the functionality of the subsystem or the components used for that subsystem can be improved or made more cost-effective,
- Design and development of subsystems required to make the system more user-friendly, including an automated start-up and shut-down purge system, electrolyte fill and drain system, and a system or equipment required to neutralize spent electrolyte,
- Full integration of the DHS system components into the fuel cell overall design envelope, and modifications to the controller and control software,
- Final design and packaging of the system, including an oxygen sphere so that the system is fully capable of underwater testing by DCIEM,
- A series of performance tests designed to evaluate the performance of the ADM, with input provided by the end-user.

As part of this work, it may be possible to adapt the overall design to meet other applications identified by DCIEM or FCT for this power source. Where possible, the ADM unit(s) would be constructed so as to minimize the cost of applying this power source to these applications. This modular approach would aid in the development of this power source, as a larger market for the fuel cell would help justify the cost of production of the system, and increase its overall marketability.

A detailed breakdown of the proposed work required to develop an ADM is included as Appendix B.

APPENDIX A – TEST PLAN

Test Duration: 6 Hours

Electrolyte: 6.5 molar KOH w/ 0.02 mol stannate - running solids free

Electrolyte Volume: 3.3 L

O2 Flow Rate: 0.7161 L/min (with 10% bleed rate, at 12 V)

O2 Pressure: 10" W.G. above ambient (measured at regulator output)

Purge Gas: Nitrogen/CO2

Stack Information: 9 cells, ~12 V, ~250W electrical, ~200 W Net Thermal

Measured Variables:

	Measurement Range	Measurement Device	Output to Data logger	Data logger Channel
Stack Voltage	10.2V-13.8V 8 V minimum	Direct connection used with calibration for line loss	+/- 20 V	302
Stack Current	32 A maximum	50 A Shunt	+/- 50 mV	303
H2O Flow Rate	1 L /min	Labcor Turbine Type U-32703-56	0-5 V	304
KOH Temperature	~50 deg C	T-Type Thermocouple	T-Type Input	305
Stack Inlet Temperature	~40 deg C	T-Type Thermocouple	T-Type Input	306
Stack Outlet Temperature	45-60 deg C	T-Type Thermocouple	T-Type Input	307

- A HP datalogger will be used to generate a binary file for input to Excel.

Safety Considerations:

- All team members to wear safety glasses when monitoring test
- When handling caustic, team members must wear lab coats, face shields and protective gloves.
- The purge system must be checked prior to starting test, there must be at least 250 psi in the tank before starting. Purge functionality must be tested.

- The system should be purged for 5 min at 2 L/min prior to starting the test.
- The purge system should be run for 15 min after the test at 2 L/min.
- H2 vent must be placed under water when running on bench top.

Test Procedure:

1. Check purge tank to ensure 250 psi min. Turn on purge to 2 L/min and leave on for 5 min
2. Check O_2 tank level (750 psi min)
3. Fill and turn on Heater Unit to 40 deg C
4. Fill stack with 3.3 L of prepared KOH (4.197 kg)
5. Turn on KOH pump by closing SW1 and supplying 12VDC to the shore power lead
6. When KOH temperature is at least 35 deg, switch 3 way valves from purge to run position.
7. Monitor stack output, watch for leaks, check H2 evolution rate.
8. When voltage has come up, disconnect shore power and allow unit to power itself
9. When KOH temperature is approx. 40 deg, turn on load, and apply enough current to drop the voltage down to 10V. This will heat the stack up at the maximum rate.
10. Running current should be between 20 and 25 A.
11. When stack has run successfully for ½ hour, place stack underwater in pool. Stack must be placed at least 15cm below the surface of the water.
12. Monitor stack output, watch for leaks, check H2 evolution rate.
13. The test should be stopped when:
    - Stack outlet temperature is greater than 60 deg C.
    - Stack Voltage drops below 8.0 V

Shutdown Procedure:

1. Keep unit under water.
2. Reduce electrical load to zero.
3. Turn both 3 way valves to the purge setting

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APPENDIX B – RECOMMENDATIONS FOR FURTHER WORK

This section outlines the work that should be carried out as part of the development and trials of an Advanced Development Module (ADM). This shall form the basis of the proposal to develop an ADM. This work will be broken into the following categories:

- Prototype system testing,
- Subsystem development, including
  - Design improvements and additions,
  - Integration of DHS into fuel cell system,
- Final design and packaging,
- Performance testing.

B.1 Prototype System Testing

The prototype system would be used to quantify the overall system performance, as well as to identify and verify system design improvements, where possible. The work would be broken down as follows:

1) Procurement of a modified DHS from Delta Temax,
2) Design and implementation of improved insulation for the prototype unit,
3) Performance testing to quantify system performance over a range of output power requirements, idle modes, etc.
4) Evaluation of subsystems under development (start-up and shut-down purge) and/or subsystems under development or improvement

By using the prototype system to evaluate design changes or improvements, the development risk for the ADM is significantly reduced. As such, this testing would be carried out throughout this phase of the program, where subsystem design activities warranted further performance testing. The prototype unit would be maintained and supported throughout this phase of the work.

B.2 Subsystem Development

A number of subsystems need to be improved or more fully integrated into the ADM, and some subsystems have not yet been developed or implemented in the prototype unit. This section details the subsystem development work required in the design of the ADM.

B.2.1 Cell Stack

Analysis and development work is required in the design and manufacturing of the cell stack. In general, further development can be broken down into the following areas:

- Evaluation of various stack design options, including a fully bonded stack, alternate cell materials, molded cell designs, and any other design options that may result in a more cost-effective and reliable cell stack design,
- Manufacturing and testing of various stack designs using the prototype unit,
- Design and procurement of sufficient tooling in order to manufacture cells and cell stacks in quantity,
- Production of finished drawings of all cell stack components,
- Manufacturing of cell stacks for evaluation testing and to support field trials.

B.2.2 Thermal Management

The performance of the thermal management subsystem proved adequate during prototype testing: Further development is limited, but includes the following:

- Performance testing to quan

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14 ABSTRACT

(U) This report describes the second phase of a program to develop a Diver Heating System (DHS). The technology selected for the power supply was the aluminum-oxygen fuel cell. An aluminum anode is oxidized in the presence potassium hydroxide electrolyte when supplied by oxygen from a conventional diver's oxygen storage and regulator equipment. The fuel cell is approximately 50% efficient. The heat rejected to the electrolyte is recovered in a heat exchanger, and the electrical output is also converted to heat.

During this phase of the work, a pumped system was developed, after a trade-off analysis showed that a pumped system had significant cost and logistical advantages over the type of cell stack developed in phase one of the work. The electrochemical performance of the cell stack and the technical feasibility of this type and design of fuel cell had been proven in phase one of the work, but the development of a pumped system represented a significant departure from the previous phase 1 work.

The system was designed, built and successfully tested in the presence of the scientific authority. The system was tested underwater, and delivered 500 Watts of thermal output for a period of 5 ½ hours. The test demonstrated the integration of all of the required subsystems of the fuel cell, but did not include integration of the fuel cell with the diver heating system (DHS) developed by Delta Temax. Delta Temax were unable to provide a unit tailored to the 12 Volt output of the fuel cell in time for system integration and final testing. However, integration with the heating system is not considered a technical risk, and can be accomplished in the next phase of the work.

This report summarizes the design, subsystem development, and test results for the fuel cell. Also included are recommendations for further work, which will form the basis for a proposal for the phase 3 activities required to develop an Advanced Design Module.

15 KEYWORDS, DESCRIPTORS or IDENTIFIERS

(U) Diver heating
Fuel Cells
Aluminum
self-contained diving
power supplies
battery

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